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BUFFALO, NEW YORK 14221

PROJECT FOG DROPS
INVESTIGATION OF WARM FOG PROPERTIES AND FOG MODIFICATION CONCEPTS

UNPUBLISHED PRELIMINARY DATA

QUARTERLY PROGRESS REPORT

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I. INTRODUCTION

The Office of Aeronautical Research of the National Aeronautics and Space Administration has authorized this Laboratory, under Contract No. NASr-156, to investigate warm fog properties and possible fog modification concepts. The program to date has emphasized analytical and experimental work on:

1. Models of the micro- and macroscopic properties of warm fogs.

2. The characteristics of aerosol droplets and means of favorably altering these properties.

3. The construction of apparatus for simulating certain fog conditions.

4. Experimental alteration of the growth and evaporation rate of otherwise stable aerosol droplets.

5. Formulation of fog modification concepts based on the above findings, as well as a review of other possible techniques.

6. Assessment of the supercooled fog problem in the United States and specification of the geographic areas where an operational seeding program might be practical.

This report briefly describes accomplishments of the period 1 October, 1964 to 1 January 1965 which represents the second quarter of the second year contract extension. Plans for the next quarter are outlined.

II. DISCUSSION

A. Thermal Diffusion Chamber

Development of the thermal diffusion chamber has been completed and the apparatus is currently being used on a daily basis to make atmospheric nuclei measurements. The basic design of the instrument is the same as reported in Report No. RM-1788-P-4 but some features have been improved to facilitate the nuclei counts being made. The chamber has been fitted with plane glass windows to reduce light losses and eliminate image distortion caused by the curved lucite walls. The operating height to diameter ratio of the chamber has been reduced from 1/2 as originally proposed, to 1/6. This important feature will be discussed later in the text. Exhaustive temperature measurements within the sampling volume of the chamber have shown that the full bank of 10 thermistors originally used is not required during instrument operation. With the water surfaces close together, i.e. height to diameter ratio of 1/6, a nearly linear vertical temperature profile can be assumed and measurements of temperature need only be made at the two surfaces of the water reservoirs.

We have found that with this configuration we can make accurate and reproducible measurements at supersaturations as low as 0.02%. Accuracies of approximately ±0.1% supersaturation can be achieved on a routine basis for desired supersaturations larger than 1.0% and for smaller desired values the accuracy is improved to approximately ±0.01% supersaturation.

In order to study actual droplet sizes within the test chambers we prepared glass slides with a thin layer of oil and captured cloud droplets at relatively high supersaturations (about 10%). The treated slides were placed under a prefocused microscope and photographed within 10-15 seconds of droplet capture. Because micron size droplets, even when immersed in a layer of oil, will evaporate fairly rapidly when exposed to dry air, the slides were photographed as quickly as possible after obtaining a specimen. Droplet diameters were found to be in the range 2 to 10 microns, as shown in Figure 1. These values are consistent with estimates of scattered light made with the instrument optical system and with observations of the fall velocity of droplets in the chamber.

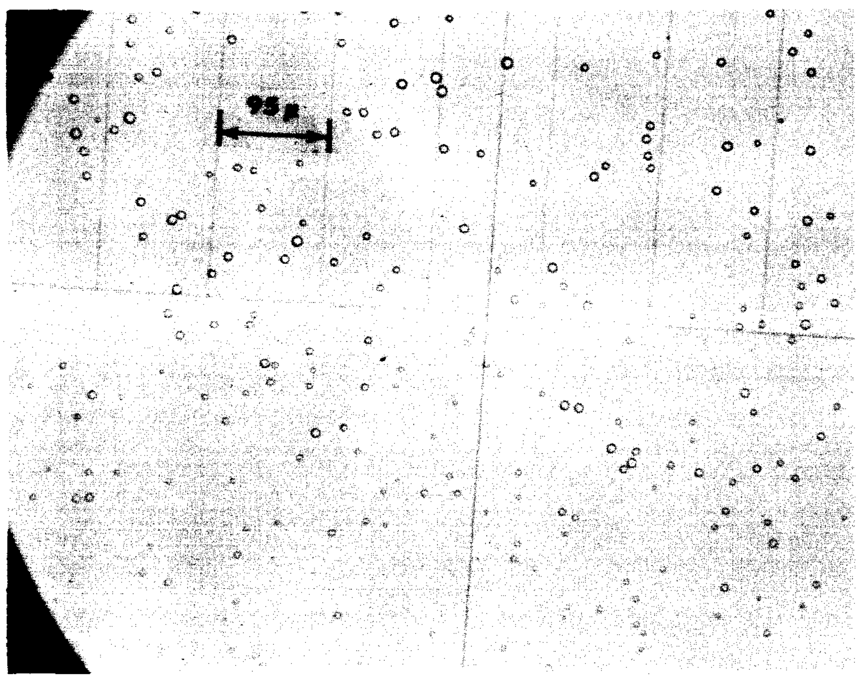

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Figure I FOG DROPLETS CAPTURED IN THERMAL DIFFUSION CHAMBER

Recently we constructed and tested a chemical diffusion chamber to determine if roughly equal numbers of nuclei could be activated in both the thermal and chemical chambers at theoretically comparable supersaturations. Photographs indicated that similar numbers of nuclei were activated.

Preliminary attempts to photograph fog droplets were made using various experimental chambers, all with height to diameter ratios of approximately 1/2. We found that, while photographs could be made at supersaturations of 5% and larger, considerable difficulty was encountered for lower supersaturations and no data could be obtained below 1% supersaturation. These data were at first interpreted as an apparent lack of sensitivity of the optical system, such that small droplets formed at 1% and lower supersaturation were not detectable. Later it was determined that under low supersaturations the excess water vapor in the vicinity of the droplets was reduced by condensation at a rate faster than it could be replaced by diffusion from the upper reservoir. Hence the ambient supersaturation was actually substantially lower than that computed from measured temperatures. This difficulty was resolved by decreasing the distance between the water surfaces so that the vapor flux was greatly increased and enough water vapor was available through molecular diffusion to maintain the calculated supersaturations.

B. Measurement of Atmospheric Nuclei

To obtain outdoor nuclei samples, the Cloud Physics Laboratory has been equipped with an air intake duct constructed of 2" copper tubing. A fan continually draws outside air through the duct and past a sampling tap, which allows the air to be aspirated into the chamber by a small vacuum pump. A three way solenoid valve has been positioned ahead of the chamber inlet to allow the sampling volume of the chamber to be flushed with nitrogen prior to admitting atmospheric nuclei. The valve also serves as an air-tight seal, preventing additional atmospheric nuclei from entering after the sample is taken. (We discovered later, that it would not be necessary to flush the chamber with nitrogen as long as a sufficient volume of outside air was passed through the chamber prior to making a measurement.)

The observational technique and sampling procedure we are using is as follows: the upper and lower water reservoir temperatures are carefully adjusted to permit the system to come to equilibrium at a predetermined supersaturation. When the desired temperature differential has been achieved, nuclei to be investigated are aspirated through the chamber at a continuous rate for 5 to 6 seconds. (It is important to avoid pressure changes within the chamber during the sampling period. Clearly, spuriously high supersaturations will prevail if a partial vacuum is created within the chamber.) Once inside the chamber the air sample is allowed to reside in the supersaturated environment, where in a few seconds, those nuclei that are activated under the existing supersaturation grow to droplet size and become visible in the sampled volume. The droplets continue to grow until they are several microns in diameter, and then settle out. Other nuclei that are not active, simply remain suspended in the sample but do not participate as observable droplets in the ensuing cloud. Photographs of fog drops are taken a moment before sedimentation begins which can be easily estimated after a little experience. Sample photographs are shown in Figure 2-5. The photographs shown have been enlarged for presentation here.

Generally, four or five samples are photographed for each supersaturation. Active nuclei are estimated from droplet counts made through an overlay which defines a sensitive portion of the photograph measuring 0.42 x 0.92 cm corresponding to a sensitive volume in the chamber of 0.072 cm^3.

From the data accumulated thus far, the following median values were observed for several pertinent supersaturations. Continued daily measurements must be made, however, before statistically significant comparisons can be made between nucleus numbers and air mass type.

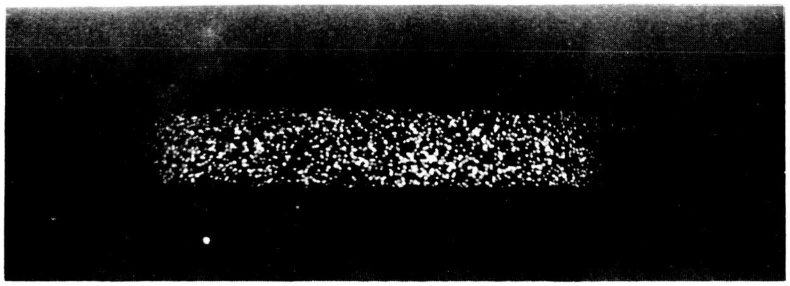

Figure 2 WATER DROPLETS FORMED AT 3.0% SUPERSATURATION 5000 DROPS/ cm^3

Figure 3 WATER DROPLETS FORMED AT 0.9% SUPERSATURATION 4200 DROPS/ cm^3

Figure 4 WATER DROPLETS FORMED AT 0.3% SUPER SATURATION 1050 DROPS/ cm^3

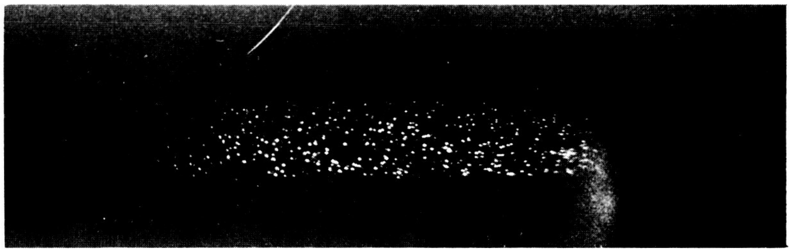

Figure 5 WATER DROPLETS FORMED AT 0.1% SUPER SATURATION 500 DROPLETS/ cm^3

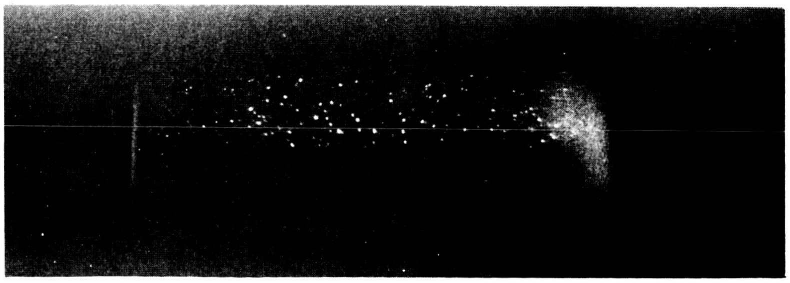

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Table I

% Supersaturation	Mean Number of Nuclei/cm^3
3.0	6100
0.9	3750
0.3	1050
0.2	790
0.1	430

Even though measurements are made on a daily basis, almost all of the samples to date have been taken on overcast days; on two occasions a few snow flurries were reported in the area. Widespread precipitation has been observed only once in the past few weeks and on this occasion a brisk wind from Metropolitan Buffalo partially obscured the removal of nuclei normally associated with rainfall. At all supersaturations, nuclei counts were highest when the wind was from the city. With observations continuing on a daily basis much needed data will become available for analysis during the next few weeks.

C. Natural Fog Measurements

Slides treated with a gelatin layer are being used to obtain permanent replicas of the drop size distribution in natural advective and radiation fogs occurring in the Buffalo area. Such experiments will contribute to the meager information now available on drop size distributions in fog. To date, only three advection fogs have been observed and replicas made. The drop diameters in these fogs were found (as expected from long exposure to a supersaturated environment) to be several microns larger than droplets formed in the thermal diffusion chamber. Hopefully, we will be able to combine this initial study of natural fogs with detailed studies of individual natural hydrometeors in the diffusion chamber. We are considering experiments in which growth characteristics of natural fog droplets captured on spider filaments will be determined. After allowing drops to evaporate, the residue can be reactivated and droplet growth observed under natural environmental conditions that are reproduced in the diffusion chamber.

D. Fog Frequency Distribution in the Continental United States

During the first year of this project we conducted a brief climatology of supercooled fogs in the Continental United States and concluded in the First Annual Report No. RM-1788-P-4 that such fog constituted a significant problem in the pacific northwest but was of only minor concern in other portions of the country. In accordance with plans for this year we have extended the climatology to include warm fogs by conducting a somewhat detailed study of the distribution of the mean number of days on which heavy fog (visibility of 1/4 mile or less)occurred at 256 reporting stations in the Continental United States. Results of this study are reported here.

Briefly this survey shows that warm fog is a significant problem over 60% of the Continental United States with 160 out of 256 stations reporting heavy fog more than twenty days per year. Fifty of these stations ($\sim$ 20% of the total) report more than 35 days of heavy fog per year. The mean fog frequency per reporting station in the Continental United States is 27 days per year. These numbers emphasize the severity of the fog problem. The discussion that follows defines the geographical regions of the United States where the fog problem is most severe.

The source of the data for this study was the U. S. Department of Commerce, Weather Bureau, Local Climatological data summaries for 256 first order weather stations in the Continental United States. These statistics are based upon the total length of record at each station and represent widely differing numbers of years of observation. Some stations have as few as two years of record, while the frequencies of heavy fog for other stations are based upon as many as sixty to eighty years of observation. Most of the data covers the period through 1963, however many years this may be. A few stations had long records for earlier years, but a change in station location reduced the record to ten years or less in 1963. Earlier data for these stations were acquired and compared with the more current, shorter period statistics.

By nature, fog is largely a localized weather phenomenon, because the causative factors of moisture and cooling are greatly influenced by local terrain and geography. Nevertheless, large geographical areas have sufficiently similar character to allow analysis of fog frequency distribution for intervals of 5 to 10 days/year. Figure 6 is a conventional isopleth analysis of the average annual number of days with heavy fog in the Continental United States. In most areas, local effects appear as secondary random departures from the general pattern.

The fundamental assumption for such an analysis is the continuous distribution of the analyzed parameter. Although this assumption is not completely valid for fog frequency, the analysis demonstrates that it is a reasonable approximation for much of the United States for the data density available. The most notable exceptions are the evident discontinuities along the Sierra Nevada Mountains and the central Appalachian Mountains, and the numerous singularities among coastal stations such as New Orleans, La., Point Magoo, Calif., Duluth, Minn., and Nantucket.

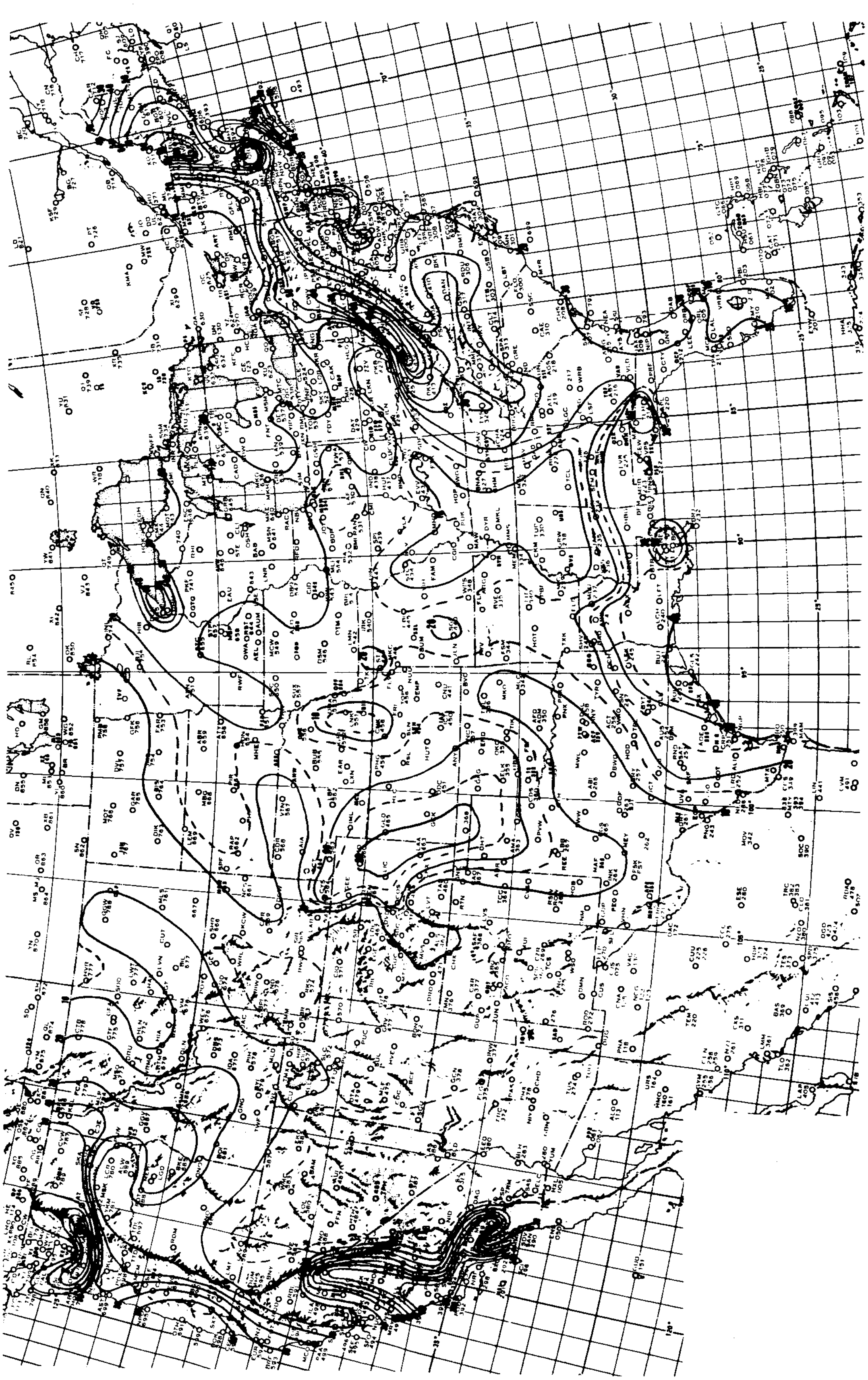

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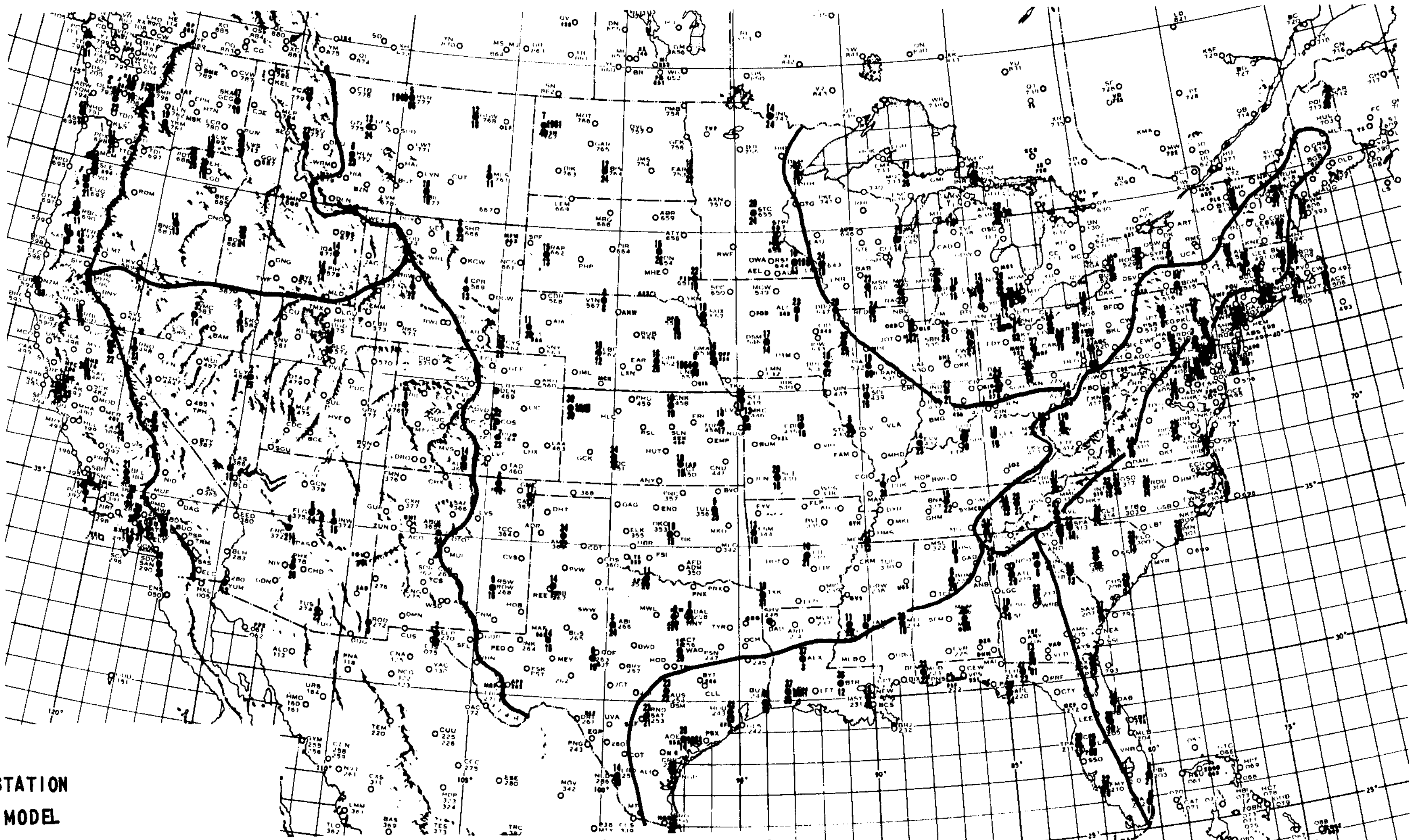
Figure 6 MEAN ANNUAL HEAVY FOG FREQUENCY (DAYS PER YEAR)

The solid isopleths in Figure 6 are drawn for intervals of 10 days. Most of the area east of the Sierra Nevada and Cascade Mountains and west of the Tennessee Valley can be analyzed to twice this detail (dashed 5-day isopleths) without appreciable degeneration of the pattern. On the other hand along the pacific coast and in the central Appalachians, fog is such a localized phenomenon that with the station density available, even the ten day isopleths cannot be located with any certainty. We therefore sought other means for presenting data.

In the sequence of different types of analyses that were tried, it became evident that the United States could be divided into seven regions (shown in Figure 7) of common terrain and geographic properties that are strongly related to fog frequency. Data were grouped according to these areas and histograms, showing the number of stations reporting heavy fog frequencies within five day frequency intervals, were plotted for each. These histograms and one covering the entire Continental United States are presented in normalized form in Figures 8 through 12. To the extent that the reporting stations are representative samples, the figures may be interpreted in terms of the fraction of the total area of the region that is characterized by the fog frequency indicated. A brief discussion of the characteristics that control fog frequency distribution within each region is presented in the text.

West Coast

The area west of the Sierra Nevada and Cascade Mountains is under the influence of the Pacific Ocean and the orographic lift provided by the mountains. As a consequence, heavy fog frequency is generally high. The irregular terrain and varying proximity to the ocean causes a wide spread in heavy fog frequencies. The greatest frequencies occur along the shore of southern California and at the stations located high in the mountains, particularly in northern California and Oregon.



STATION MODEL

F - MEAN ANNUAL NUMBER OF DAYS WITH HEAVY FOG (1/4 MILE OR LESS)
N - NUMBER OF YEARS OF RECORD UPON WHICH F OR F' IS BASED
YEAR - LAST YEAR OF RECORD IF OTHER THAN 1963 (YEAR REFERS TO F' AND N' IF INCLUDED)
F' - SAME AS F FOR EARLIER PERIOD
N' - LENGTH OF EARLIER PERIOD RECORD

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Figure 7 BOUNDARIES OF FOG CLIMATIC REGIONS AND STATION FREQUENCY DATA

Sierra Nevada to the Rocky Mountains

This arid region is cut off from moisture by mountain barriers both east and west. The lack of moisture causes a narrow, uniformly low, fog-frequency distribution. No station in this region averages over 10 days of heavy fog per year, while the majority experience 5 days or less per year. The broadening influence of irregular terrain is ineffective here due to the general lack of moisture.

Cascade to the Rocky Mountains

This area is characterized by mountains separated by broad, flat valleys. Moisture, though not abundant, is adequately supplied from modest precipitation and preserved through lower temperatures than those to the south. As a result, all stations in this region experience an average of at least 11 days of heavy fog per year. Most of the weather stations in this region are located in the valleys, but the variety of terrain still causes a broad spread of heavy fog frequencies.

Great Plains and Mississippi Valley

The uniform terrain and moderate moisture characteristics of this broad region are responsible for the narrow, modest, heavy-fog-frequency distribution displayed in Figure 10a. The principal water source is the Gulf of Mexico but no large water bodies directly influence fog formation in this area. The foothills of the Rocky Mountains tend to broaden the frequency distribution. Five of the seven stations reporting over 20 days of heavy fog per year are located along the eastern slopes of the Rocky Mountains where orographic effects are evident.

Great Lakes Area

The influence of the Great Lakes extends south of the lakes themselves to an ill-defined border with the Great Plains and Mississippi Valley region. To the east, the Appalachians form a more distinct border of the Great Lakes area. Heavy fog is understandably higher near the Great Lakes than in the Great Plains. The spread of fog frequencies is also greater in this area. The highest fog frequencies are near the water, but fog frequency does not vary as much with distance from the water as it does between stations at comparable distances from water.

Appalachian Mountains

The Appalachian Mountains region resembles the West Coast region in many ways. Both are areas of irregular terrain and substantial moisture, with orographic lift of west to east flow. As a result, the fog frequency distributions in the two regions are very similar, both showing high average incidence and large frequency spread. The annual number of days with heavy fog in the Appalachians varies from a low of 22 days to a high of 307 days. In general, the greatest fog frequency is found to the west of the highest terrain due to orographic lift of the predominant westerly winds.

Atlantic and Gulf Coasts

These two coastal regions were at first treated separately, but because of the strong similarity of their respective fog-frequency distributions they may be combined into a single region. Both coasts display a moderately broad frequency distribution around a relatively high modal frequency. However, despite the proximity of large bodies of water the frequency spread is substantially less than that of either the Appalachian Mountain region or the west coast areas -- where irregular terrain creates widely diverse local fog-producing conditions. The one extreme local influence in this area is found in the Nantucket and Block Island area where the heavy fog frequency is about twice that of the other stations along these coasts.

Local environmental differences are not the only explanation for the apparent discrepancies between adjacent stations. Both long and short-term mean annual heavy fog-frequency statistics were acquired for fourteen stations whose 1963 means were based upon ten years of record or less. In most instances where such a double record was acquired, the long period statistics report fewer days with heavy fog than the shorter period. The following is a comparison between long and short-term mean annual number of days with heavy fog for the fourteen stations for which such data are available.

Tallahassee, Florida	55 days/yr.	for 2 yrs.	41 days/yr	for 22 yrs.
Lake Charles, Louisiana	51	2	37	23
Lansing, Michigan	24	9	13	45
Rochester, Minnesota	38	3	16	11
Saint Louis, Missouri	10	6	8	22
Lincoln, Nebraska	7	8	5	58
Atlantic City, New Jersey	43	5	21	53
Williston, North Dakota	9	2	7	45
Toledo, Ohio	20	8	8	83
Fort Worth, Texas	10	10	8	55
Alpena, Michigan	18	4	20	45
Glasgow, Montana	11	8	12	18
Havre, Montana	5	3	5	56
Victoria, Texas	24	2	28	14

Although there are several possible explanations for these differences between long and short-term means -- change in observing procedure, climatic change, increased industrialization, poor choice of airport or observing sites, etc. -- the available data are sufficient to ascertain the actual cause. The mere existance of this discrepancy coupled with the wide variation in length of record for the 256 stations used in the analysis does, however, suggest that length of record may contribute to the variation between stations in a given area.

Separation of this effect and that of local environmental conditions is difficult or impossible where two stations in close proximity have both substantially different lengths of record and reported fog frequency. Detroit, Michigan is one example of this problem with two stations separated by twenty miles with 5 and 30 years of record and mean annual heavy fog frequencies of 25 and 12 days respectively.

Despite the difficulties imposed by the type of data available and the largely local nature of fog, the analysis provides significant insight into the nationwide climatology of fog. The differences in mean and modal frequency of heavy fog and the differences in the degree of local influence from region to region are real and quite pronounced. It is obvious that heavy fog is not a problem in the southwestern mountain region and only a moderate problem in the Great Plains. On the other hand, fog is most frequent and quite local in nature along the West Coast, in the Appalachian Mountains and along the New England Coast. Along the Gulf and Atlantic Coasts and in the Great Lakes region fog is quite frequent (more than 20 days per year on the average) and local effects do not seem to be as significant as in other areas of high incidence.

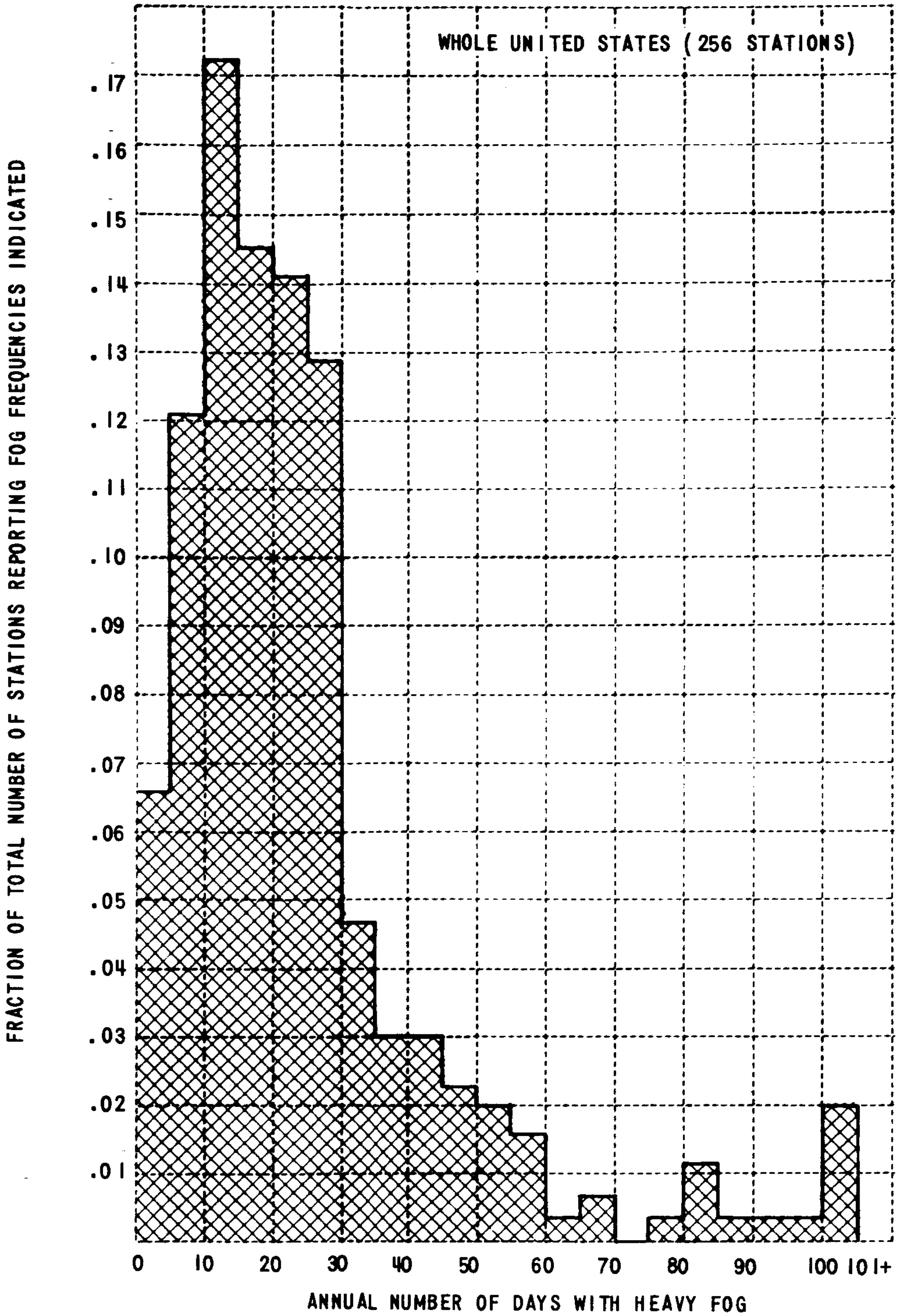

WHOLE UNITED STATES (256 STATIONS)
FRACTION OF TOTAL NUMBER OF STATIONS REPORTING FOG FREQUENCIES INDICATED
.17
.16
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
10
20
30
40
50
60
70
80
90
100
101+
ANNUAL NUMBER OF DAYS WITH HEAVY FOG

Figure 8

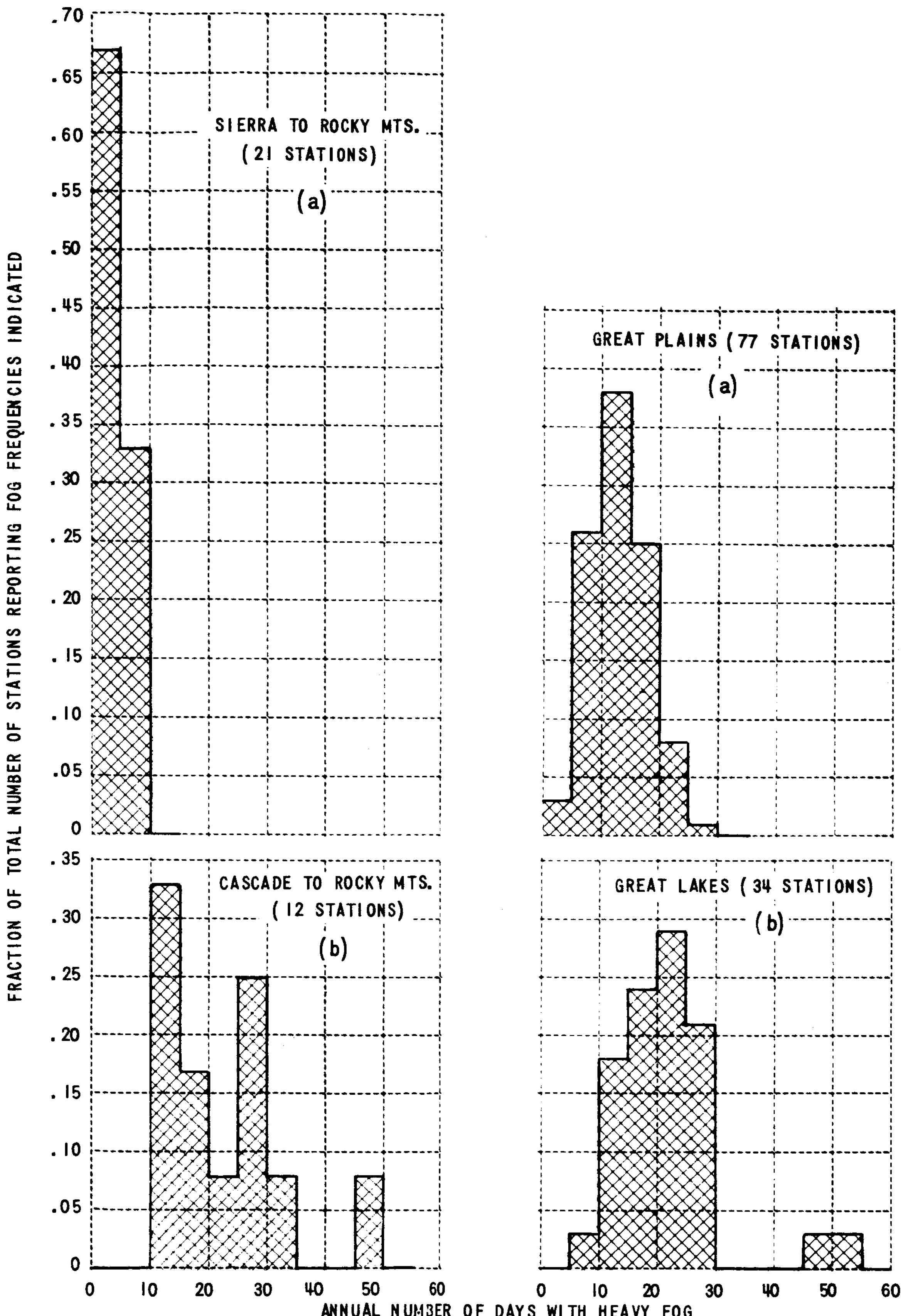


Figure 9

Figure 10

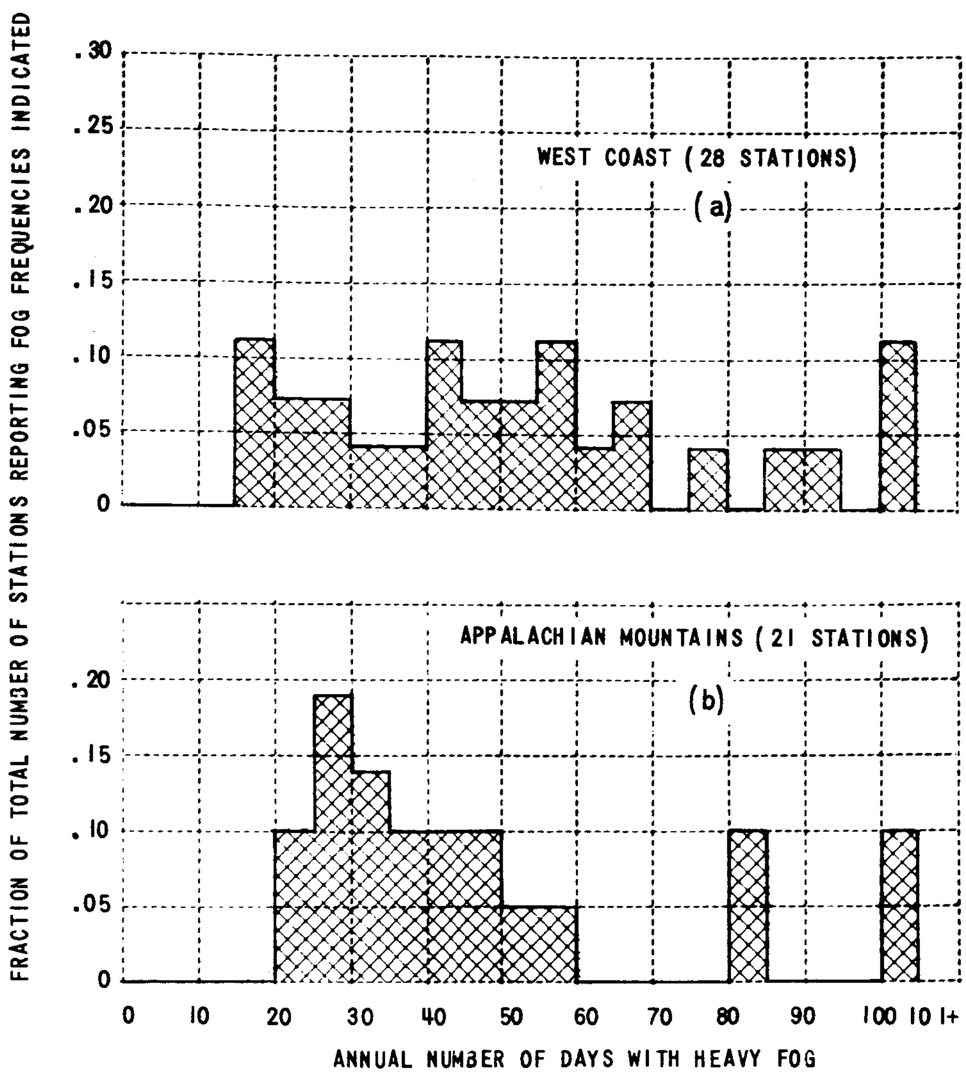
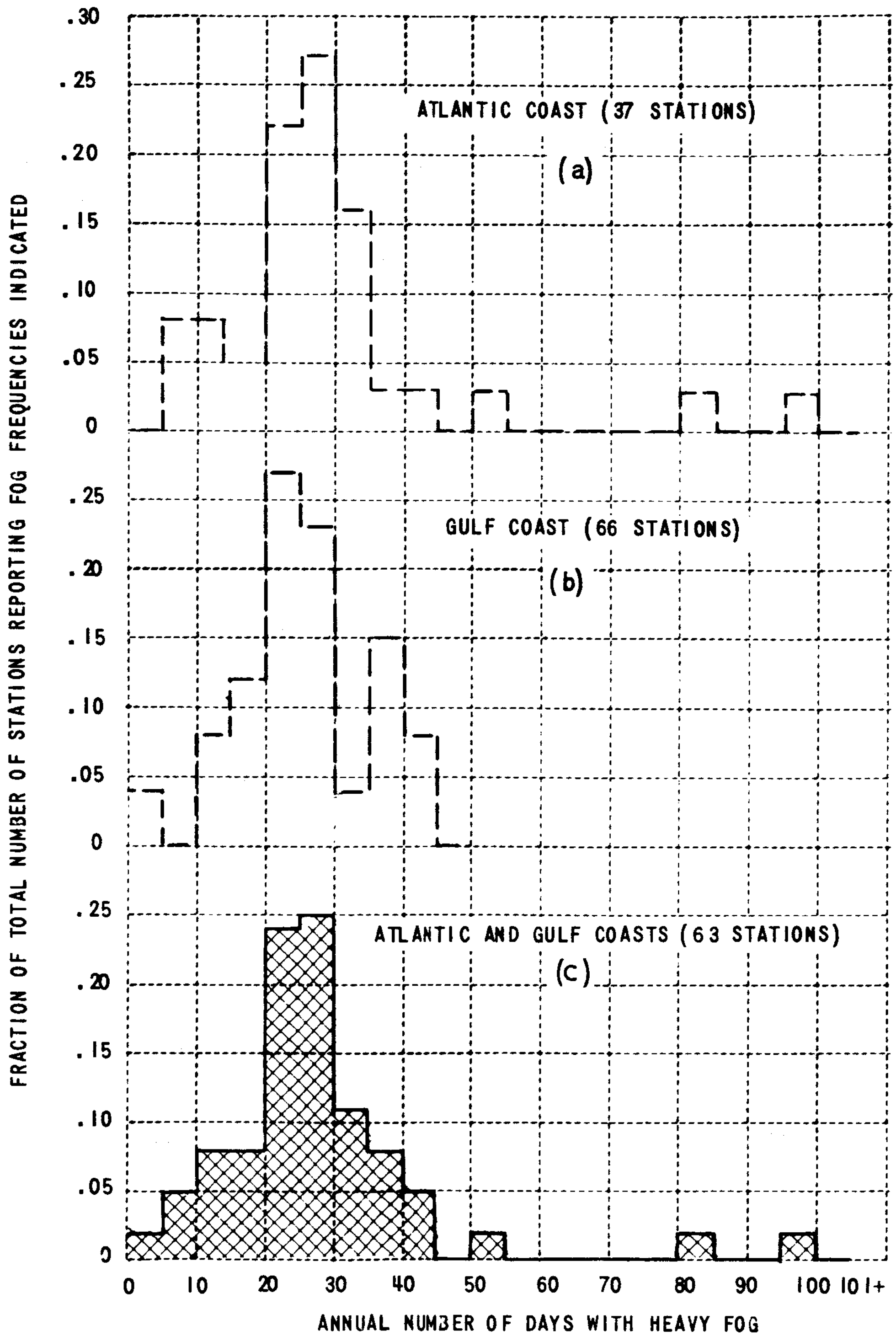

FRACTION OF TOTAL NUMBER OF STATIONS REPORTING FOG FREQUENCIES INDICATED
.30
.25
.20
.15
.10
.05
0
WEST COAST (28 STATIONS)
(a)
APPALACHIAN MOUNTAINS (21 STATIONS)
(b)
.20
.15
.10
.05
0
0
10
20
30
40
50
60
70
80
90
100
101+
ANNUAL NUMBER OF DAYS WITH HEAVY FOG

Figure 11



FRACTION OF TOTAL NUMBER OF STATIONS REPORTING FOG FREQUENCIES INDICATED
ATLANTIC COAST (37 STATIONS)
(a)
GULF COAST (66 STATIONS)
(b)
ATLANTIC AND GULF COASTS (63 STATIONS)
(c)
.30
.25
.20
.15
.10
.05
0
0
10
20
30
40
50
60
70
80
90
100
101+
ANNUAL NUMBER OF DAYS WITH HEAVY FOG

Figure 12

III. FUTURE PLANS

1. Continue routine nuclei measurements on a daily basis to gather sufficient data for a statistical survey as outlined.

2. Commence laboratory studies of the effect of certain ionic surfactants on droplet coalescence rates.

3. Attempt to develop monolayer coating techniques for large populations of droplets produced in our cold box.

IV. REFERENCE

Twomey, S., 1959: The Nuclei of Natural Cloud Formation - Part I, Geof. Pura E Appl. - Milano, 43, 227.